Identification and analysis of changes in patient behavior that lead to falls from the bed

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Abstract

Patients fall out of their beds frequently in hospitals, and such incidents are a critical issue because they often lead to serious accidents. Accidents of patient falling out of beds have increased with increasing numbers of the hospitalized elderly. Although bed sensors are commonly used as a fall-preventive measure in hospitals, these sensors cannot prevent accidents. We hypothesized that if bed sensors can monitor patients’ behavioral changes continuously like vital sensors, nurses will be able to understand patient behaviors from the recorded data and provide appropriate care, thus decreasing patient falls. A three-dimensional measurement system was then developed. With this system, the position, movement, direction, and velocity of patients can be measured in a three-dimensional space in a non-contact, noninvasive manner. Using this system, we measured long-term behaviors of patients in bed. The analysis results allowed us to identify the behavior changes leading to a patient’s fall from bed. In addition, we quantified how behavioral changes in acute-phase patients change over several weeks after hospitalization. We believe that these quantified data will be useful in daily patient care and in evaluation of nursing-care plans.

Key words: medical safety, bed falls, sensor, three-dimensional measurement

Introduction

The U.S. Agency for Healthcare Research and Quality (AHRQ) has announced that falls are the most frequent type of incidents in hospitals. Reports state that in acute-care hospitals¹, fall accidents are occurring 1.3–8.9 times/1000 beds per day. In Japan, approximately 2% of the total number of hospitalized patients have fall accidents². Falls frequently occur both in acute-phase and chronic-phase patients, often leading to serious fatal accidents requiring emergency measures. Of the fall accidents that occur, the percentage of falling out of beds is high. According to Tashiro et al.³, 51% falls occur around beds.

Although many medical institutions and researchers have long researched on measures preventing and mitigating falls out of beds, the numbers of fall accidents have not decreased⁴. Various sensors have been introduced by hospitals to detect patient movements as a measurement to mitigate patient’s fall accidents from beds. Specific sensors are shown in Table 1.

Reliability in the effectiveness of bed sensors is low. According to a clinical study by Shorr et al.⁵, fall incidences did not differ between patients using bed sensors and those not using sensors. The stated cause was because patients had already fallen when the sensor was triggered.

Furthermore, the sensor is designed to detect the instant when patient starts moving and does not have...
functions to detect when the patient moves his/her body slightly and when parts of the body or bed linens touch the sensor. Once the sensor reacts, unless it is deactivated by a nurse, subsequent alarms also will not be detected. Thus, there are many false positives and false negatives.

Hence, erroneous data are commonly generated. According to Hatsukari et al.\(^6\), detection rate of rising was 60.0%, the false-positive rate was 50.4%, detection rate of sitting position was 70.1%, and the false-positive rate was 15.5%.

In our survey of bed sensors in four medical institutions, responses included issues in the functionality of sensors such as positively reacting to even when rolling over and taking deep breaths, inadvertent touches of the sensor (e.g., by the arms of the patient), and generating false positives because of poor sensitivity. Responses were obtained on the invasiveness and danger of sensors, such as mat sensors causing bedsores as they are set on the bed mat, patients slipping on the pad, and tripping over the floor-mat sensors. There are also issues on patients’ behavior preventing sensors to function: patients intentionally touching or taking away the sensor, deliberately trying to leave the bed by crossing unmonitored fences or footboards, necessitating unstable postures and risk of falls.

Thus, reliability is low with many false negatives and false positives because of complex reasons of functions of sensors and the patient behavior create many false negatives and false positives.

Recent studies measure patient movements by using three-dimensional optical sensors, research developments featuring track positions and posture of patients by using image processing. Although image processing detects patient’s behavior, it cannot recognize the patient who are covered with bedclothes, nor can it identify high-risk behaviors from various patient movements or predict subsequent behaviors even if position and posture can be identified. There is a limit in preventing patients from falling out of their beds even with increased sensor precision.

To prevent patients from falling out of their beds, we hypothesize that sensor systems continuously measuring patient’s condition, identifying and notifying increased risk behaviors that require intervention, in a manner similar to that of vital sensors, are more effective than ones detecting patient’s movements immediately before they fall.

To verify the hypothesis, in this study, we have identified behavioral changes that lead to patient falls that were unclear in the past. We have also developed a sensor system that specifies and notifies potential behaviors leading to falls from patient behaviors by analyzing such behavioral changes to evaluate the effectiveness of the fall-prevention measures. This study may contribute in decreasing bed falls of patients frequently occurring as serious hospital accidents, as well as in enhancing safety of hospitalized patients, eliminating causes of fall behavior, and enhancing quality of life (QOL).

### Materials and Methods

1. **Requirements for selecting patient-monitoring systems**

Conventional sensors adopt a sensing method that detects momentary behavioral changes of patients in
bed. As described in section 1, conventional sensors have sensor-related issues on effectiveness, invasiveness, and safety, along with issues altering patient behaviors as well. Thus, we suggested that an effective method is one where a sensor is placed away from the bedside so that the patient is not able to touch it, and may continuously identify the change in patient overall movements, identifying risk behaviors that lead to falls.

Therefore, we developed a system, thinking that it is necessary to measure the movement of the patient in three dimensions.

The requirements for the risk-behavior-monitoring system are as follows:

1. No invasiveness to patients or researchers
2. Protection of patient privacy
3. Placement of the sensor out of reach of the patient
4. Monitoring of all behaviors of patients in bed; the patient cannot avoid the sensor
5. 24-h measurements
6. Monitoring of patients in the dark
7. Distinction of safe and risk behaviors
8. Selection of risk behaviors only and recording of measurement results
9. Visualization of records for confirmation
10. Continuous recording of patient behaviors for sufficient amount of time (records observing subsequent behavioral changes is important than that of moment of identification)

2. Selected patient risk-behavior detection and recording system

We selected a sensor according to the requirements listed in section 2.

Specifically, a time-of-flight (TOF) infrared sensor, which is no contact-type as well as noninvasive type was chosen because it can be used to monitor an object several meters away. The TOF sensor device irradiates the target object with an infrared laser, and measures the time required for the laser to reach the object, be reflected, and reach the detector of the sensor device.

Accordingly, the distance to the object \( L \) is calculated as follows using the speed of light \( c \) and time \( t \) which takes from irradiating infrared laser from the device to return to the light receiving part.

\[
L = \frac{c}{2t} \quad \cdots (1.1)
\]

This sensor was chosen because it has the following advantages in addition to meeting the requirements listed in 2.1.

a) It meets Voluntary Control Council for Interference by Information Technology Equipment (VCCI), Federal Communications Commission (FCC), and Council of Europe (CE) in class A, is not invasive to patients or researchers even in a hospital, and does not affect other medical devices.

b) The resolution of the detector is low at 25,488 pixels, which is sufficient for recognition of human movements, but is insufficient to recognize the face, thus protecting patient privacy.

c) The maximum measurable distance is 4.0 m, which is sufficient to conduct sensing from a position that is out of patient reach.

d) The TOF sensor has horizontal and vertical view angles of 70° and 55°, respectively, and all behaviors can be monitored with appropriate placement.

e) The sensor uses an 850-nm near-infrared laser and detector and can hence be used in the dark.

f) A three-dimensional measurement library is available because measurement algorithms can be developed.

This sensor used can measure the position in an environment of 100,000 lux or less. Therefore, when using this sensor in the hospital room during the day, there is no need to block the light with a curtain.

We developed a software program to convert sensor-derived three-dimensional position information to patient position information on the bed, and subsequently identified risk behaviors among body movements.

We investigated patent data measuring patients on bed. As a result, we found 2 patents. One is measuring with two cameras from different direction⁷ and the other is measured respiration in three dimensions⁸. However, we could not find a patent similar to our study.

3. Experiment of monitoring patients’ movements in clinic

The purpose of this experiment was to empirically test if a behavior requiring intervention by a nurse can be detected in constantly changing patient behavior continuously measured with the device. More specifically, we developed a system capable of the following and conducted a verification experiment.

1. To continuously monitor a patient in bed, we
use a three-dimensional measurement system, isolate behaviors that lead to falls from all patient movements, notify a computer kept in the nurse center and record.

(2) Series of behaviors that show how the patient fell are recorded as video data.

(3) Data from long-term observations are quantitatively analyzed and patient behavior changes after hospitalization are evaluated.

1) Subjects

Clinical study was conducted in Keno Tokorozawa Hospital in Tokorozawa city, Saitama. Four subjects were observed for a total of 87 days from April to June 2013 and in July 2014. One patient was observed at a time. Patients with high fall risk were selected for the study according to fall risk assessments at the hospital. The study was approved by the ethics committee of Keno Tokorozawa Hospital (March 2013), and patients’ family members signed consent forms after receiving a formal explanation of the clinical study from a physician at Keno Tokorozawa Hospital. Experiments and assessments were carried out in collaboration with nurses and eight physical therapists at Keno Tokorozawa Hospital.

2) Measurement system setting

The present experimental system transmits three-dimensional space coordinate data (X, Y, and Z) from the TOF sensor to a computer at 60 frames/s. The computer software recognizes the three-dimensional position, surface area quantity, and the direction of movement of a moving object in the space at all times. Six arbitrary detection zones were set (Fig. 1) in a space above the mattress, in a left space and a right space of the bed, and in a space above the footboard so that risk behaviors of the moving patient can be detected (Fig. 2). These were defined in consultation with nurses. Detection zones 1, 4, and 6 were used to detect level-1 risk, zone 3 was used to detect level-2 risk, and zones 2 and 5 were used to detect level-3 risk (Fig. 2).

The three behavior risk levels were defined by nurses and physical therapists from Keno Tokorozawa Hospital using the actual bed based on previously encountered behaviors that led to falls.

The sensor continuously monitors the bed and its surroundings and the computer algorithm that we developed always recognizes the object on the bed based on three-dimensional coordinate data from the sensor. Subsequently, the sensor activates an alarm and records a video at 15 frames/s for up to 20s when an object with surface area of ≥20,000 mm² moves toward the outside of the bed and stops for at least 1 s. The video length (20s) was chosen based on preliminary experiments that were performed by nurses and occupational therapists. Video recording was stopped automatically when the object in the alarm zone returned to the non-alarm zone, and thus provided records of how patients entered detection zones and changed behaviors thereafter.

Recorded data included descriptions of (1) frame heights and widths and numbers of frames/s and (2) coordinate correction coefficients (rotation angles and distances of movements along X, Y, and Z axes), and the origin was set for distance data because the sensor was positioned in an oblique direction from the patient.

The sensor location and the computer in the nurse station are shown in Fig. 3. Data communications between the patient room and the nurse station were transmitted through an encrypted wireless LAN. The personal computer in the nurse station had an alarm lamp and sound that were activated when the patient entered an alarm zone. Attending nurses then confirmed the validity of the alarm visually on the display. Nurses were able to check patient status on the computer in the nurse station at any time regardless of the alarm status.

Measurements with an existing sensor were performed concurrently to compare sensors. The control sensor detects uprising based on changes in patient body weight loads on the bed, and was used...
with the built-in device. The control device was linked to the nurse-call device in the patient room. The nurse-call main unit in the nurse station also records and displays month, day, hour, minute, and second of events upon activation of the control device alarm. This system was not linked with the nurse-call system, and the clock of the research system was matched with that of the nurse-call main unit.

The present monitoring system was used to record and store time and video data in the personal computer for all events that activated the alarm. Because the nurse-call system cannot deliver alarm data to an external device, nurses took screen shots of the nurse-call main unit.

3 ) Method for analysis of changes in patient behavior

Collected video data were reproduced on the personal computer and which stage of status of risk levels the sensor reacted and subsequent patient behaviors (Fig. 2) were visually confirmed.

( 1 ) Sensor performance was compared with the control sensor according to risk-level settings for detection zones, and false positives were eliminated.

( 2 ) Short-term changes in patient behaviors were recorded in seconds, medium-term changes were recorded in days, and long-term changes were recorded over the entire hospital stay.

The control device was checked to confirm the

Fig. 2 Estimate the behavior of the patient

Fig. 3 Equipment configuration
4) Subjects

Subject characteristics are shown in Table 2. All patients were of advanced age and had decreased muscle strength. However, subjects differed in conditions such as disturbances of consciousness and drug use, and they were divided into groups according to the requirement of a fall-prevention belt and the ability to walk independently to a restroom and other places.

Three lower limits of detection were used and were expressed as distances from the mattress surface, because the sensor reacts even to kneeling, depending on patient’s physique, if the detection zone is set low in the vicinity of the mattress surface. Different detection limits were also necessary because patients had different requirements of early detection as determined on the basis of fall risk assessments at the time of admission.

Specifically, the limit was set at 30 cm for patient A, 40 cm for patient B, and 50 cm for patients C and D.

**Experimental Results**

Patient measurements are shown in Table 3. Although only four patients were monitored, data from 1195 sensor reactions were obtained from 2088 h of measurement. Total hours of measurement varied between patients because they were hospitalized for different lengths of time.

Initially, the experimental sensor and the control sensor were compared according to whether risk-level settings for detection zones were as planned, and whether false positives could be eliminated.

The risk-behavior-detection rate of the research system was low for patient A. This 68-year-old patient was suffering from delirium; however, the patient had greater muscle strength and stamina than other older patients and often acted violently on the bed. The patient was restless, and often engaged in behaviors such as stretching out his hand to detection zones, stretching out his feet, standing with his knees, and throwing out the futon. The detection rate for this patient was low because these objects entered a detection area and were detected. Hence, we concluded that detection of risk behaviors using this research system is dependent on the patient state.

Accordingly, detection rates for patients B-D were 76%–94% because the patients behaved as nurses and occupational therapists predicted.

The control device detects whether the body weight loaded on the bed is more than a threshold, and its alarm is activated when the load is below a certain level.

The control device failed to detect any risk

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**Table 2** Status of patients’ condition

<table>
<thead>
<tr>
<th>Patients</th>
<th>Gender</th>
<th>Age</th>
<th>Fall history</th>
<th>Wobble</th>
<th>Muscle weakness</th>
<th>Disturbance of consciousness</th>
<th>Using drugs</th>
<th>Use of fall-prevention belt</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>male</td>
<td>66</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Memory loss, Disorientation, Dangerous behavior</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>B</td>
<td>female</td>
<td>79</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Memory loss, Disorientation, Dangerous behavior</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>C</td>
<td>female</td>
<td>87</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>D</td>
<td>male</td>
<td>85</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>N</td>
</tr>
</tbody>
</table>

**Table 3** Measurement result

<table>
<thead>
<tr>
<th>Patients</th>
<th>Gender</th>
<th>Age</th>
<th>Experimental period (days)</th>
<th>Reaction times of the research system (times)</th>
<th>Detection rate of dangerous behaviors</th>
<th>Reaction times of the control equipment (times)</th>
<th>Detection rate of dangerous behaviors</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>male</td>
<td>66</td>
<td>27</td>
<td>432</td>
<td>16%</td>
<td>NG</td>
<td>NG</td>
</tr>
<tr>
<td>B</td>
<td>female</td>
<td>79</td>
<td>36</td>
<td>417</td>
<td>76%</td>
<td>10</td>
<td>1.8%</td>
</tr>
<tr>
<td>C</td>
<td>female</td>
<td>87</td>
<td>13</td>
<td>172</td>
<td>94%</td>
<td>NG</td>
<td>NG</td>
</tr>
<tr>
<td>D</td>
<td>male</td>
<td>85</td>
<td>12</td>
<td>174</td>
<td>90%</td>
<td>197</td>
<td>30%</td>
</tr>
</tbody>
</table>
behaviors of patients A and C because the threshold for alarm activation was inappropriate. According to the director of nursing who participated in the study, this threshold must be set for each patient and cannot be optimized because the set value is not displayed, the configuration panel is difficult to operate, and the device does not react when the patient body weight is low.

In addition, it was found that short-term changes in patient behavior and those over the whole hospitalization period were detected (Figs. 4 and 5).

Initially, images from a video were used to visualize changes in the state of patient B for up to 20s (Fig. 4). Because the control device did not detect any risk behaviors, the nurse call was not activated, and the nurses were unaware that the patient was at risk of fall for 3h.

Over this time period, risk behaviors in patient B (Fig. 4) did not continue but changed constantly, and were consistent with those observed in the other subjects.

This series of repeated level-3 risk behaviors could have been altered if a nurse had intervened at around 2 o’clock.

Moreover, we analyzed patient’s changes during the hospitalization period.

In analyses of changes in patient behavior over the entire hospitalization period from admission to discharge (Fig. 5), patient D frequently engaged in risk behaviors immediately after hospitalization, but showed decreased risk behaviors over time. The vertical axis of the graph indicates the number of risk occurrences.
behaviors per day, and indicates changes for 12 days from July 13 to 24, 2014. The straight line indicates a fitted curve. This multiple correlation coefficient is 0.832.

**Discussion**

In this study, we discovered two major findings. The present patient measurements from a three-dimensional infrared TOF sensor made it possible to noninvasively monitor every movement of a patient in bed during the day or night. The system also avoided the false positives that are associated with patient–sensor contact, because the sensor was placed outside the reach of patient’s hand during the experimental period. Furthermore, we also enabled to monitor risk levels of patient behaviors by setting six three-dimensional detection areas on and around the bed. This approach completely eliminated false positives because of intentional or unintentional patient–sensor contacts. In addition, patients were unable to avoid the sensor while leaving the bed, and false negatives were also decreased. Finally, no invasions or risks to patients were present because the sensor was not attached to the bed, and we were able to quantify risk and visualize the patient state.

Conventional sensors have no clear detection criteria and simply provide a gives ON/OFF binary alarm signals when a cord is pulled because of a patient movement, or in response to a body-weight shift, and gives no clear indication of whether the signal was triggered by patients’ risk behavior or how risky the patient behavior was. Because of the lack of information on the level of urgency, a general approaches is that to detect even a slight body movement so that risk behaviors can be identified as early as possible. This is why false positives have been frequently occurring. False positives and false negatives were frequent also because the sensing sensitivity for the ON/OFF signal is difficult to set.

The present system detects patient behaviors with corresponding risk levels according to defined criteria, and can be used to convey three risk levels. Accordingly, nurses need to be aware of level-1 risk behaviors for some patients but need not intervene until level-3 risk behaviors are detected for other patients. Therefore, the ability to adjust the timing of interventions for each patient by changing risk-level settings will likely increase patient safety and flexibility in care prioritization.

In addition, patient–specific time zones in which risk behaviors frequently occur could be visualized by quantifying patient behaviors. In particular, patient D engaged in risk behaviors frequently during the day and data from days 13–16 (Fig. 6) showed high frequencies of risk behaviors from 10 am to 12 pm (Fig. 5, denotes night hours). Moreover, risk behaviors were frequent during the night and day of day 16.

These data indicate that patient behaviors can be monitored in detailed measurements of individual patients at times of high risk, likely facilitating fall prevention by identifying when care is most needed.

In addition, the present system preserves patient dignity and safety during visualization of patient behaviors.

The guide to zero physical restraint of the Ministry of Health, Labour and Welfare states that "accident prevention effects are not necessarily clear".

Images ①, ②, and ③ in Fig. 7 are of patient B wearing a fall-prevention belt at her waist, and show that the fall-prevention belt effectively limited the range of patient movement and prevented her body from crossing the fence. However, in images ④, ⑤, and ⑥ the belt has come off the patient’s body allowing free movement and increased fall risk. Therefore, although physical restraints are insensitive to patient dignity, the effectiveness of the restraint for fall prevention was confirmed in the present visualization. Hence, although the restraint is confining for the
patient it protected the patient’s life.

These observations warrant further assessments of the appropriateness of restraints in larger studies, and the development of criteria for defining their necessity.

Conclusion

In this study, we conducted the following three new methods.

(1) Detection method of patient precursor behavior

This system measures all patient behaviors on the bed by setting up a three-dimensional area in the upper, left, right, front and rear of the bed, and a part of the body is detected by entering those area. On the other hand, the existing sensors are developed to detect the behavior of any one patient, such as the action of raising the upper body of the patient and the state of the sitting posture, as shown in Table 1.

(2) Novelty of setting the risk level

Depending on the level of consciousness of the patient and physical abilities, the risk levels of falling may vary. Conventional sensors can only detect certain behaviors, so these sensors can not set the levels. Therefore, it is unclear whether the risk of the patient falling will increase after detection of these sensors. As a result, there are many false positives.

So, we set three steps risk levels of patient falls together with nurses and occupational therapists. By setting the risk levels, we can expect that the timing of different interventions will be revealed for each individual patient, preventing falls from the bed and reducing false positives.

(3) Recording function available

The system records changes in the behavior of patients on the bed. This has the function to analyze changes by level. Nurses expect to be able to evaluate the quality of nursing by using this system.

As a result, (1) patient risk behaviors were measured as a whole in a noninvasive manner and various risk behaviors were detected; (2) patient behaviors, which have been unclear to date, were visualized by analyzing recorded and stored videos of patients’ behavior; and (3) changes in patient behaviors were quantified by setting out risk-behavior criteria.

Continuous monitoring and evaluation of patient behaviors provide a guide for optimizing health care, and this is the first study to report this. Moreover, although discussion of restriction of patients freedom have been an emotional one, by visualizing the safety of patients, we hope that the system will outset a scientific discussion of pros and cons based on evidence.

No guidelines on detecting patient behavior have been devised for bed sensors, and it has been unclear what one should detect to prevent patients from falling.

In the future, we suggest that the use of visual data from three-dimensional measurements will allow medical staff and equipment technologists to enhance discussions under a common understanding, leading...
to a development of better bed sensors with fewer false positives and false negatives.

It should be noted that this study was conducted in a single hospital with results evaluated by four medical institutions, including collaborating hospitals, thus making a room for improvement. We expect that the results of this study will have groundbreaking effects, expanding discussion on scientific fall-prevention measures.

References


2) Japan Red Cross Nagoya Daini Hospital HP Inpatients Falls 2016.10.20. [http://www.nagoya2.jrc.or.jp/1/QL/5.html]


キーメッセージ

1. 今回の研究は看護・介護のどのような問題をテーマにしているのか？
   研究を行うきっかけとなったことはどのようなことか？
   患者のベッドからの転落問題。世界的にベッドからの転落事故は大きな問題である。この課題を、工学技術を使い解決できないかと考えたことがきっかけとなった。
2. この研究成果が看護・介護にどのように貢献できるのか？あるいは、将来的に貢献できることは何か？
   患者が傷害を受ける、患者の家族や担当看護師が心的傷害を受けない、転落による訴訟が起こらない、治療費が不要になる、転落による入院の長期化が防げる、偽陽性による看護師の負担が減らせる
3. 今後どのような技術が必要になるのか？
   予兆行動を明確にするためのセンシング技術と画像処理技術。